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Evaluating asymmetry in prosthetic gait with step-length asymmetry alone is flawed

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ABSTRACT

Prosthetic gait is often asymmetric in step length, but the direction of this asymmetry varies inconsistently across amputees. This situation is akin to that seen in stroke patients, where step-length asymmetry has been shown to be the additive result of asymmetries in trunk progression and asymmetries in forward foot placement relative to the trunk. The present study examined the validity of this notion in three trans-tibial and seven trans-femoral amputees wearing a unilateral prosthesis while walking over a walkway at a comfortable and slower-than-comfortable speed. The latter manipulation was added to examine the expectation that the magnitude of the trunk-progression asymmetry – attributable to a weaker propulsion generating capacity on the prosthetic side – would be smaller when walking slower because of the diminished propulsion demands. Step length, forward foot placement relative to the trunk, and trunk progression of prosthetic and non-prosthetic steps, as well as asymmetries therein, were quantified. The direction of step-length and forward foot placement asymmetries varied inconsistently across (but consistently within) participants. As expected, step-length asymmetry depended on the combination of asymmetries in forward foot placement and trunk progression, with a smaller contribution of trunk-progression asymmetry at slow speed. These results extend our previous finding for hemiplegic patients that an analysis of gait asymmetry in terms of step length alone is flawed to prosthetic gait, implying that knowledge of asymmetries in trunk progression and forward foot placement relative to the trunk is required to help elucidate the contribution of underlying impairments (viz. propulsion generating capacity) and adopted compensations on prosthetic gait asymmetry.

1. Introduction

Gait after a unilateral lower-limb amputation is often asymmetric, as evidenced by shorter stance and longer swing phases for the prosthetic than non-prosthetic leg and asymmetries in double stance support durations accompanied by a reduced propulsion force generated by the prosthetic leg [1–7]. Typically, also step length differs between sides [3,6,8–12]. Prosthetic step length represents the fore-after distance between non-prosthetic and subsequent prosthetic foot placement positions (conversely for non-prosthetic step length). However, the direction of step-length asymmetry varies inconsistently across amputees [13,14], resulting in the absence of systematic difference between prosthetic and non-prosthetic step lengths within a sample [1,2,14–16]. Thus, even though step length is one of the most commonly used parameters in prosthetic gait analysis [7], step-length asymmetries are difficult to interpret in amputees.

Recently, Roerdink and Beek [17] partitioned step-length asymmetry (SLA) of post-stroke gait into trunk-progression asymmetry (TPA) and asymmetry in forward foot placement relative to the trunk (FFPA; see also [18]). They found that TPA and FFPA accounted for SLA in an additive manner and that TPA and FFPA were negatively correlated, implying that their relative contribution was responsible for directional variations in SLA. To illustrate these findings for prosthetic gait, Fig. 1 depicts three different relative contributions of asymmetries in trunk progression and forward foot placement and their effect on step-length asymmetry (see Table 1 for an overview of the employed acronyms and their definition). The larger prosthetic than non-prosthetic step in Fig. 1A is attributable to an asymmetry in trunk progression combined with symmetric forward foot placement relative to the trunk. This situation matches with the weaker propulsion generating capacity of the prosthetic leg [5,12,13,16,19–22] and/or hip extension limitation due to socket-ischium mechanical

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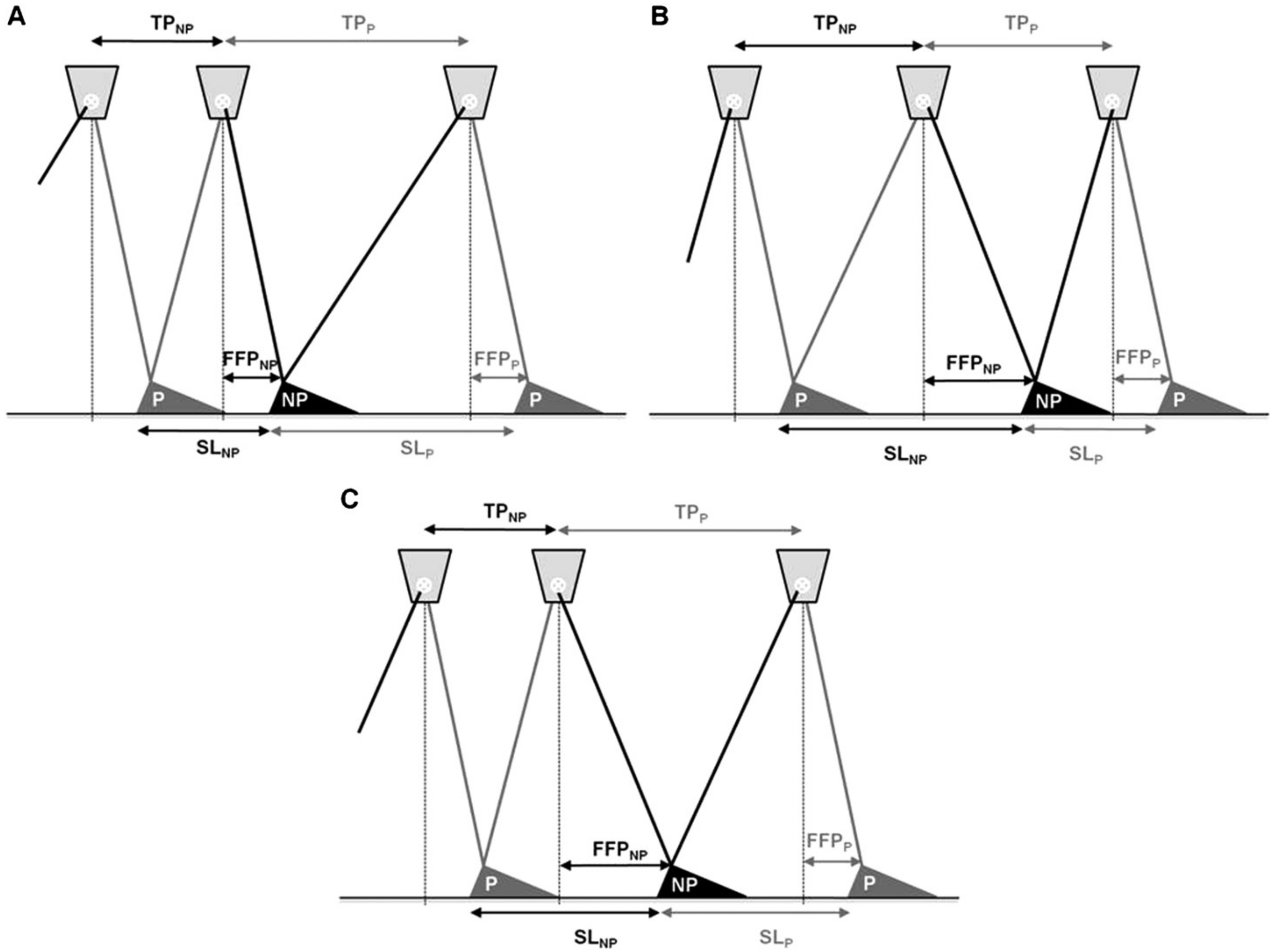

Fig. 1. Schematic representation of trunk progression (TP) and forward foot placement relative to the trunk (FFP) determinants of asymmetry in step length (SL) between prosthetic (P) and non-prosthetic (NP) steps. (A) $SL_P > SL_{NP}$, with $TP_P > TP_{NP}$ and $FFP_P = FFP_{NP}$, (B) $SL_P < SL_{NP}$ with $TP_P = TP_{NP}$ and $FFP_P < FFP_{NP}$, and (C) $SL_P = SL_{NP}$, with $TP_P > TP_{NP}$ and $FFP_P < FFP_{NP}$.

interaction [14]. As a consequence, the trunk does not displace as far forward of the supporting foot during prosthetic single limb support, resulting in a shorter non-prosthetic than prosthetic step. Alternatively, the shorter prosthetic than non-prosthetic step in Fig. 1B is accounted for by an asymmetry in forward foot placement relative to the trunk at foot strike combined with symmetric trunk progression. This situation concurs with the reduced ability to swing the prosthetic leg forward during the non-prosthetic stance phase due to, for example, the loss of muscle function following amputation, altered inertial properties of the prosthetic leg, and/or socket-prosthesis geometry on the affected side [11,14,15,23,24]. The reported negative correlation between TPA and FFPA [17] indicates that their individual effects on SLA (as outlined in Fig. 1A and B, respectively) are typically somewhat annulled. The limit of this cancellation is depicted in Fig. 1C: overall gait is highly asymmetric, whereas step lengths are symmetric because TPA and FFPA are similar in magnitude but opposite in direction.

The relative contributions of both components to step-length asymmetry have not been examined in prosthetic gait. The present study aims to explore the relationship between SLA, TPA and FFPA in a heterogeneous group of lower-limb amputees walking at self-selected comfortable and slower-than-comfortable speeds. The speed manipulation is included as gait asymmetry varies with speed [2,4,5,15,25,26]. As in hemiplegic gait [17], we expected TPA and FFPA to account for SLA in an additive manner (SLA = TPA + FFPA) and potential inconsistencies in the direction of SLA to depend on their relative contribution. Second, considering that propulsion demands are smaller at slower walking speeds, we anticipated a smaller contribution of the weaker propulsion generating capacity on the prosthetic side to gait asymmetry. For this reason, we expected a smaller TPA magnitude at slow speed.

2. Methods

2.1. Participants

Seven unilateral trans-femoral and three unilateral trans-tibial amputees were recruited, all proficient users of their own prosthesis and free of co-morbidities that could influence walking ability or the ability to understand instructions. Table 2 lists participant and prosthetic characteristics. Participants provided written informed consent before data collection.

2.2. Procedure

Timed up-and-go and 10-m walk tests were performed to reveal participants' walking ability (Table 2). To assess gait kinematics, participants were instructed to walk along a 7.5 m long walkway for four trials. In the first and third trial, participants were instructed to walk at their comfortable walking speed and in the second and fourth trial at a slower-than-comfortable speed. The position of light-emitting diodes attached to the heels of the participants' shoes and to a horizontal rigid beam attached to a waist belt (representing the pelvic marker) was recorded (100 Hz) with a motion registration system (Optotrak 3020, Northern Digital Inc., Waterloo).

Table 1
Acronyms, units and definitions of gait parameters related to step length (SL), trunk progression (TP), and forward foot placement relative to the trunk (FFP).

Acronym	Unit	Definition
SL_P	m	Prosthetic step length, defined as the distance between anterior–posterior positions of a prosthetic heel strike following a non-prosthetic heel strike
SL_{NP}	m	Non-prosthetic step length, defined as the distance between anterior–posterior positions of a non-prosthetic heel strike following a prosthetic heel strike
SLA	%	Step-length asymmetry, defined as $100\% \times (SL_P - SL_{NP})/(SL_P + SL_{NP})$
|SLA|	%	Magnitude of step-length asymmetry, defined as the absolute value of SLA
TP_P	m	Trunk progression during the prosthetic step, defined as the anterior–posterior distance traveled by the pelvic marker during the prosthetic step (i.e., time interval between prosthetic heel strike following a non-prosthetic heel strike)
TP_{NP}	m	Trunk progression during the non-prosthetic step, defined as the distance traveled by the pelvic marker during the non-prosthetic step (i.e., time interval between non-prosthetic heel strike following a prosthetic heel strike)
TPA	%	Trunk-progression asymmetry, defined as $100\% \times (TP_P - TP_{NP})/(TP_P + TP_{NP})$
|TPA|	%	Magnitude of trunk-progression asymmetry, defined as the absolute value of TPA
FFP_P	m	Forward prosthetic foot placement relative to the trunk, defined as the anterior–posterior difference between the heel marker of the prosthetic foot and the pelvic marker at times of prosthetic heel strike
FFP_{NP}	m	Forward non-prosthetic foot placement relative to the trunk, defined as the anterior–posterior difference between the heel marker of the non-prosthetic foot and the pelvic marker at times of non-prosthetic heel strike
FFPA	%	Forward foot placement asymmetry, defined as $100\% \times (FFP_P - FFP_{NP})/(FFP_P + FFP_{NP})$
|FFPA|	%	Magnitude of forward foot placement asymmetry, defined as the absolute value of FFPA

Table 2
Individual participant and prosthesis characteristics and clinimetrics.

Characteristics	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Gender (M/F)	M	M	F	M	M	M	F	M	M	M
Age (years)	63	50	62	55	68	29	68	48	68	51
Height (cm)	178	198	161	186	185	182	164	172	178	185
Weight (kg)	95	95	67	108	93	95	61	74	71	114
Amputation side (L/R)	R	R	L	L	L	L	L	R	L	L
Time since amputation (months)	14	62	18	96	648	12	24	9	578	79
Time since current prosthesis (months)	8	12	15	29	60	6	24	5	60	72
Amputation cause (V/T)	V	V	V	V	T	T	V	T	T	T
Prosthetics										
Amputation level (TF/TT)	TF	TF	TF	TF	TF	TT	TT	TT	TF	TF
Knee	a	a	b	c	d	-	-	-	e	f
Ankle/foot	g	h	h	g	i	j	h	k	h	l
Clinimetrics										
Timed up-and-go test (s)	16	18	15	16	14	6	11	8	10	12
10-m timed walking test (m/s)	1.00	0.92	0.97	1.19	0.92	1.44	1.17	1.42	1.06	1.19

Abbreviations: M, male; F, female; L, left; R, right; TF, trans-femoral; TT, trans-tibial; V, vascular; T, traumatic; a, Otto Bock 3R60; b, MediPro OFM1; c, Otto Bock 3R33; d, Nabtesco Hybrid Knee NI-C311, e, Otto Bock 3R106; f, Otto Bock C-Leg; g, Endolite Multiflex foot; h, Otto Bock 1D10/1D11; i, Otto Bock 1C30 Trias; j, Össur Vari-Flex with EVO; k, Össur Flex-Foot Assure; l, Otto Bock C-Walk 1C40.

2.3. Analysis

Gait was analyzed between 2.5 and 6.5 m in order to minimize acceleration and deceleration effects at the start and end of the walkway, respectively. Time indices of heel strikes of the prosthetic and non-prosthetic legs were determined by selecting the moment at which the vertical position of the associated heel marker reached its minimum [27]. Only full gait cycles starting with a prosthetic heel strike were included (2–5 strides per trial) for the determination of speed, stride length and cadence. We further calculated step length, trunk progression and forward foot placement relative to the trunk for prosthetic and non-prosthetic steps, as well as asymmetries therein, as defined in Table 1 (see also Fig. 1). An asymmetry index of 0% indicates perfect symmetry; the magnitude represents the degree of asymmetry and the sign indicates the direction of the asymmetry. Positive indices indicate larger prosthetic step length or greater trunk progression or forward foot placement during the prosthetic step. Asymmetry indices were considered asymmetric if they fell outside control reference ranges, set by absolute asymmetry values of 4.5% [17].

Data were averaged over the two trials. Speed (slow vs. comfortable) and side (prosthetic vs. non-prosthetic) effects were examined with separate paired-samples *t*-tests ($p < 0.05$). The relation between the three asymmetry indices was examined with Pearson's correlation.

3. Results

3.1. Effect of walking speed on gait parameters

Participants walked significantly slower in the slow-speed trials (mean 0.81 m/s, SD = 0.11) than in the comfortable-speed trials (1.03 m/s (SD = 0.14); $t(9) = 8.46$, $p < 0.001$), accompanied by a slower cadence (89.4 steps/min (SD = 9.6) vs. 101.8 steps/min (SD = 8.9); $t(9) = 5.96$, $p < 0.001$) and a shorter stride length (1.08 m (SD = 0.10) vs. 1.20 m (SD = 0.15); $t(9) = 5.82$, $p < 0.001$).[1]

3.2. Asymmetry indices varied inconsistently across participants

The direction and magnitude of the asymmetry indices varied inconsistently across participants, in particular SLA and FFPA (Fig. 2). This observation was corroborated by the lack of a systematic difference between SL_P and SL_{NP} and between FFP_P and FFP_{NP}, irrespective of speed. In contrast, the trunk was displaced farther forward during the prosthetic step (i.e., during the non-prosthetic stance phase) for both slow (TP_P vs. TP_{NP}: 0.56 m (SD = 0.06) vs. 0.52 m (SD = 0.05); $t(9) = 2.31$, $p < 0.05$) and comfortable (0.63 m (SD = 0.08) vs. 0.58 m (SD = 0.08); $t(9) = 2.26$, $p < 0.05$) speeds.

[1] Likewise, prosthetic and non-prosthetic step lengths were both significantly shorter for slow than for comfortable speeds (SL_P: 0.54 m (SD = 0.07) vs. 0.61 m (SD = 0.10 m), $t(9) = 5.56$, $p < 0.001$; SL_{NP}:0.54 m (SD = 0.07) vs. 0.60 m (SD = 0.10), $t(9) = 4.82$, $p < 0.001$). The same was true for prosthetic and non-prosthetic trunk progression (TP_P: 0.56 m (SD = 0.06) vs. 0.63 m (SD = 0.08), $t(9) = 6.62$, $p < 0.001$; TP_{NP}: 0.52 m (SD = 0.05) vs. 0.58 m (SD = 0.08), $t(9) = 4.88$, $p < 0.001$) and forward foot placement (FFP_P: 0.36 m (SD = 0.05) vs. 0.38 m (SD = 0.07), $t(9) = 3.36$, $p < 0.01$; FFP_{NP}: 0.38 m (SD = 0.04) vs. 0.40 m (SD = 0.04), $t(9) = 4.84$, $p < 0.001$).

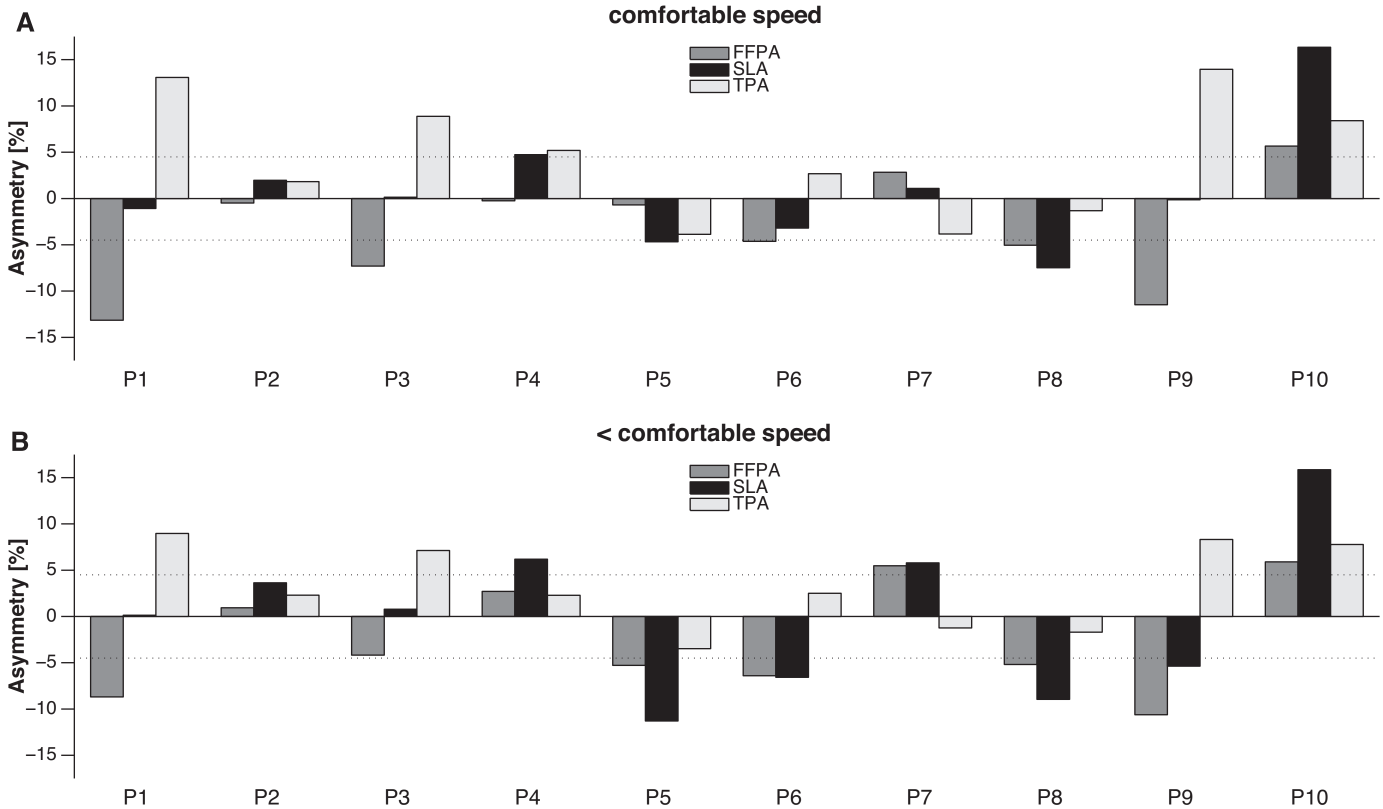

Fig. 2. Asymmetry indices for amputee participants P1–P10 for walking at (A) comfortable and (B) slower-than-comfortable walking speeds. Step-length asymmetry (SLA; centered black bars) is represented by the sum of asymmetries in forward foot placement relative to the trunk (FFPA; left-neighboring dark gray bars) and trunk progression (TPA; right-neighboring light gray bars). The three asymmetry indices were considered asymmetric if they fell outside control reference ranges, as indicated by the dotted horizontal lines.

3.3. Relation between asymmetry indices

The correlations between the three asymmetry indices are depicted in Fig. 3: TPA and FFPA were negatively correlated (Fig. 3A) while both components were positively correlated, albeit weakly, with SLA (Fig. 3B and C). SLA was strongly correlated with TPA + FFPA ($r = 0.98$; Fig. 3D), indicating that both components accounted for SLA in an additive manner.

3.4. The effect of walking speed on the magnitude of gait asymmetry

The speed manipulation had a systematic effect on the magnitude of the gait asymmetry indices, whereas their direction remained fairly consistent within participants (Fig. 2A vs. B). As expected, the magnitude of TPA (i.e., absolute value of TPA, abbreviated as |TPA|) was significantly smaller for walking at slow speed than for walking at comfortable speed (4.6% (SD = 3.1) vs. 6.3% (SD = 4.6); $t(9) = 2.68$, $p < 0.05$), whereas the opposite was found for |SLA| (6.5% (SD = 4.7) vs. 4.1% (SD = 4.9); $t(9) = 2.99$, $p < 0.05$). |FFPA| was unaffected by speed.

4. Discussion

The relationship between SLA, TPA and FFPA was explored in prosthetic gait. As expected, we found that the direction of SLA varied inconsistently across participants. Moreover, SLA was found to depend on the combination of TPA and FFPA, implying that the relative contribution of TPA and FFPA determined the direction of SLA. Finally, based on considerations of reduced propulsion demands, we expected and found a reduction in |TPA| for slow speed. The accompanying increase in |SLA| further exposed the dependency of SLA on the combination of TPA and FFPA.

4.1. Step-length asymmetry varied inconsistently across participants with unilateral lower-limb prosthesis

In the aim to demonstrate that step-length asymmetry varies inconsistently in prosthetic gait, a convenience sample of amputee patients that was heterogeneous with respect to prosthetic components and the proximo-distal level of the amputation was included in the study (Table 2). As can be seen in Fig. 2, SLA varied inconsistently over participants. Specifically, P4, P7(<comfortable), and P10 took shorter non-prosthetic than prosthetic steps (SLA > 0%), whereas P5, P6(<comfortable), P8, and P9(<comfortable) took shorter prosthetic than non-prosthetic steps (SLA < 0%). In contrast, P1, P2, P3, P6, P7, and P9 (the latter three only at comfortable speeds) exhibited SLA-values near 0%. Note that the direction of SLA also varied within trans-tibial (P6, P7 and P8) and trans-femoral (P1–P5, P9, P10) subgroups (Fig. 2).

This inconsistency in SLA is similar to previous reports on prosthetic gait [1,2,13–16]. In contrast to those studies, however, the direction and magnitude of SLA can now be assessed (both qualitatively and quantitatively) by incorporating asymmetries in trunk progression and forward foot placement relative to the trunk. Specifically, the expectation that TPA and FFPA accounted for SLA in an additive manner was supported by the strong positive correlation between SLA and TPA + FFPA (Fig. 3D), although this relation was not always perfectly obeyed.[2] Furthermore, consistent

[2] Note that the relation SLA = TPA + FFPA was not always perfectly obeyed, as evidenced by small deviations from the line of identity in Fig. 3D (see also Fig. 2). We believe this is due to the limited number of registered strides and trials, which may have hampered the reliability of the assessments because a limited number of strides included in the analyses make the analyses more vulnerable to step-to-step variation in prosthetic gait.

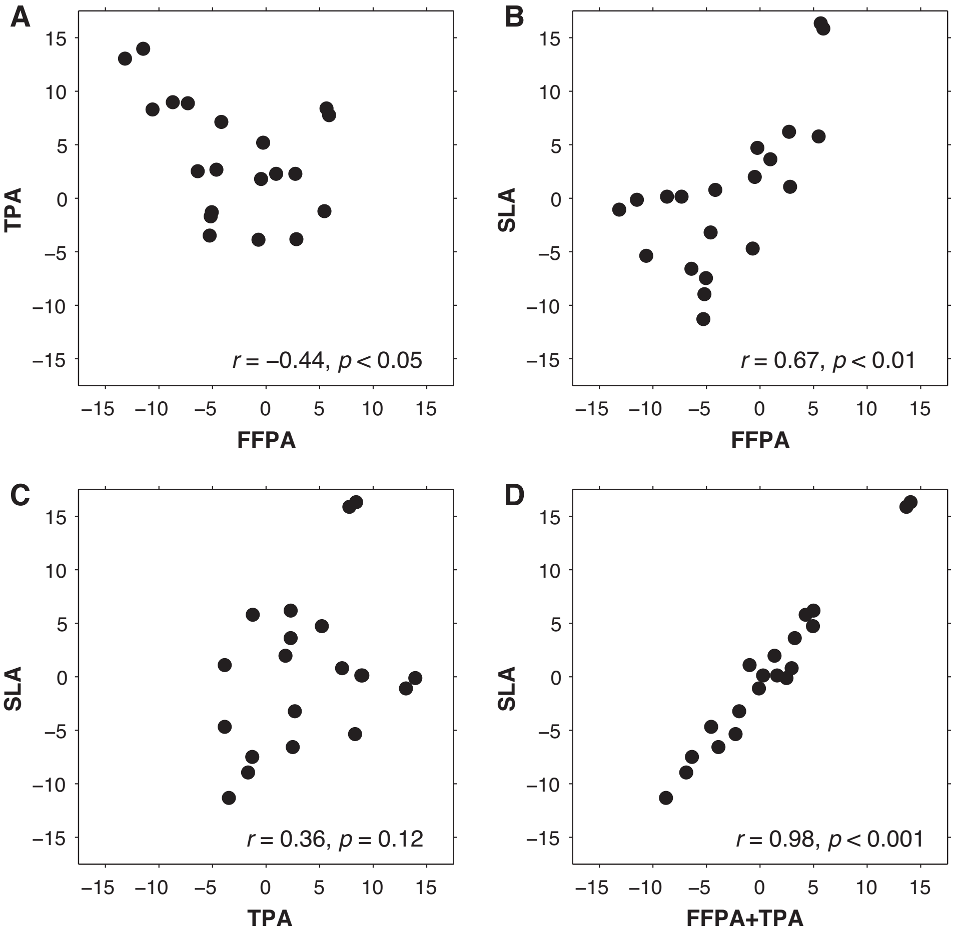

Fig. 3. Relations between the three asymmetry indices for both slow and comfortable speeds.

with the individual contributions of TPA and FFPA to SLA (as sketched in Fig. 1A and B), weak positive associations between SLA and the two components were found (Fig. 3B and C). Specifically, these positive associations indicate that the prosthetic foot is at foot strike generally placed closer to the trunk than the non-prosthetic foot (FFPA < 0%; see also [14]), while the trunk is displaced farther forward during the prosthetic step (TPA > 0%) because of the weaker propulsion generating capacity of the prosthetic leg [5,12,13,16,18–21]. These individual effects on SLA are typically somewhat annulled (Fig. 1C) due to the negative correlation between FFPA and TPA (Fig. 3A). Thus in prosthetic gait, step-length asymmetry depends on the combination of asymmetries in trunk progression and forward foot placement relative to the trunk while their individual effects on step-length asymmetry are generally softened given their negative correlation (i.e., similar to hemiplegic gait [17,18]).

4.2. Step-length asymmetry alone is insufficient for an encompassing assessment of prosthetic gait asymmetry

The overall implication of these findings is that judging the quality of prosthetic gait from the magnitude of step-length asymmetry alone is flawed. First, SLA near 0% does not necessarily imply an overall symmetric gait. From the participants with SLA near 0% only P2 walked symmetric in terms of all three asymmetry indices, whereas the remaining participants showed pronounced TPA and/or FFPA despite symmetric step lengths. Particularly, P1, P3, and P9(comfortable) exhibited pronounced asymmetries in trunk progression and forward foot placement that were opposite in direction but similar in magnitude (like Fig. 1C). As a consequence, the individual effects of TPA and FFPA on SLA were averaged out, resulting in symmetric step lengths. The same occurred for P6 and P7 at comfortable speeds, albeit that the magnitudes of TPA and FFPA were considerably smaller. These individual cases clearly show that a small step-length asymmetry can misrepresent true gait asymmetry because TPA and FFPA generally tend to offset each other.

Second, the relative contribution of TPA and FFPA is responsible for inconsistencies in the direction of SLA across participants with a lower-limb amputation (similar to hemiplegic stroke patients [17,18]). The positive SLA of P4(comfortable) resulted from an asymmetry in trunk progression, with the trunk being displaced farther forward during the prosthetic step (non-prosthetic stance; TPA > 0%), accompanied by a symmetric forward foot placement (Fig. 2A). In this example, reminiscent of Fig. 1A, SLA was thus predominantly accounted for by TPA and not FFPA. In a similar vein, the negative SLA for P5, P6 (both at slower-than-comfortable speed), and P8 was the result of a negative FFPA, implying that the prosthetic foot was placed closer to the trunk than the non-prosthetic foot, in combination with an almost symmetric trunk progression (i.e., TPA remained within symmetry boundaries; Fig. 2A and B). In this example, reminiscent of Fig. 1B, SLA was thus predominantly accounted for by FFPA and not TPA. At slow speed, P9 also exhibited a negative SLA. In this example, both trunk progression and forward foot placement were markedly asymmetric and opposite in direction (TPA > 0%, FFPA < 0%), thus to some extent softening their individual effects on SLA. However, because TPA was smaller in magnitude than FFPA, the net effect was a negative SLA. These cases exemplify (and support) our expectation that the direction of step-length asymmetry follows from the relative contributions of both components.

Third, small asymmetries in trunk progression and forward foot placement do not necessarily imply symmetric step lengths, i.e., when TPA and FFPA are relatively small in magnitude but similar in direction (P8 in Fig. 2A and B, and P4, P5 in Fig. 2B). In fact, they may even unveil a parsimonious compensatory gait pattern. P4(<comfortable) and P10, for example, seemingly adopted a pattern to attune braking impulses at foot-strike to local propulsion impairments at the prosthetic side. Note that braking is strongly determined by passive mechanics: the farther the foot is placed in front of the trunk, the greater the braking [16,20,21]. Because P4 and P10 placed their non-prosthetic foot closer to the trunk than their prosthetic foot, the associated braking was reduced and the prosthetic leg consequently had to generate less propulsion to maintain speed. Conversely, increased braking associated with a larger prosthetic forward foot placement can be readily overcome by increased propulsion generated by the non-prosthetic side. Reducing non-prosthetic forward foot placement, resulting in a positive FFPA, may thus be viewed as a parsimonious solution to maintain speed, because it calls for an unequal propulsion output per side, optimally adjusted to the reduced propulsion generating capacity of the prosthetic leg. As a consequence, SLA is prominent because FFPA and TPA were similar in direction. An analogous compensatory pattern was recently observed in hemiplegic stroke patients [17], while Rabuffetti et al. [14] adopted a comparable interpretation for their ‘outlier’ patient walking with greater non-prosthetic than prosthetic step lengths.

4.3. Walking speed affects the magnitude of trunk progression asymmetry

The speed manipulation was successful in that it induced significant changes in speed, cadence, stride length and all side-dependent gait parameters (see footnote 1): values were significantly lower for the slow speed trial. We further expected and found a reduced TPA magnitude at a slower-than-comfortable speed because the required propulsion demands then diminish. This finding clearly supports the notion of propulsion demands as a limiting factor in gait asymmetry, but not necessarily step-length asymmetry. That is, the reduction in |TPA| was accompanied by a significant increase in |SLA|, while |FFPA| remained unaffected by walking speed, thereby further testifying to their interrelationship (Fig. 3D). Moreover, the manipulation of walking speed by instruction may be an expedient means to expose such trade-offs, and may have practical relevance to physical therapy and prosthetics in that knowledge of TPA vs. FFPA may help elucidate underlying impairments (such as impaired propulsion generating capacity of the prosthetic leg). An encompassing evaluation of prosthetic or rehabilitation interventions on gait asymmetry thus calls for an examination of foot positioning in relation to trunk movements in addition to basic gait parameters such as step length, which, when analyzed in isolation, obscures rather than promotes the understanding of pathological gait.

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Conflict of interest statement

The authors have no conflict of interest to declare.

References

[1] Dingwell JB, Davis BL, Frazier DM. Use of an instrumented treadmill for real-time gait symmetry evaluation and feedback in normal and trans-tibial amputee subjects. Prosthet Orthot Int 1996;20:101–10.
[2] Isakov E, Burger H, Krajnik J, Gregoric M, Marincek C. Influence of speed on gait parameters and on symmetry in trans-tibial amputees. Prosthet Orthot Int 1996;20:153–8.
[3] Isakov E, Burger H, Krajnik J, Gregoric M, Marincek C. Double-limb support and step-length asymmetry in below-knee amputees. Scand J Rehabil Med 1997;29:75–9.
[4] Jaegers SM, Arendzen JH, de Jongh HJ. Prosthetic gait of unilateral transfemoral amputees: a kinematic study. Arch Phys Med Rehabil 1995;76:736–43.
[5] Nolan L, Wit A, Dudziñski K, Lees A, Lake M, Wychowañski M. Adjustments in gait symmetry with walking speed in trans-femoral and trans-tibial amputees. Gait Posture 2003;17:142–51.
[6] Robinson JL, Smidt GL, Arora JS. Accelerographic, temporal, and distance gait factors in below-knee amputees. Phys Ther 1977;57:898–904.
[7] Sagawa Jr Y, Turcot K, Armand S, Thevenon A, Vuillerme N, Watelain E. Biomechanics and physiological parameters during gait in lower-limb amputees: a systematic review. Gait Posture 2011;33:511–26.
[8] Barnett C, Vanicek N, Polman R, Hancock A, Brown B, Smith L, et al. Kinematic gait adaptations in unilateral transtibial amputees during rehabilitation. Prosthet Orthot Int 2009;33:135–47.
[9] Fridman A, Olna I, Isakov E. The influence of prosthetic foot alignment on trans-tibial amputee gait. Prosthet Orthot Int 2003;27:17–22.
[10] Isakov E, Keren O, Benjuya N. Trans-tibial amputee gait: time–distance parameters and EMG activity. Prosthet Orthot Int 2000;24:216–20.
[11] Mattes SJ, Martin PE, Royer TD. Walking symmetry and energy cost in persons with unilateral transtibial amputations: matching prosthetic and intact limb inertial properties. Arch Phys Med Rehabil 2000;81:561–8.
[12] Zmitrewicz RJ, Neptune RR, Walden JG, Rogers WE, Bosker GW. The effect of foot and ankle prosthetic components on braking and propulsive impulses during transtibial amputee gait. Arch Phys Med Rehabil 2006;87:1334–9.
[13] Hansen AH, Meier MR, Sessoms PH, Childress DS. The effects of prosthetic foot roll-over shape arc length on the gait of trans-tibial prosthesis users. Prosthet Orthot Int 2006;30:286–99.
[14] Rabuffetti M, Recalcati M, Ferrarin M. Trans-femoral amputee gait: socket-pelvis constraints and compensation strategies. Prosthet Orthot Int 2005;29:183–92.
[15] Sjodahl C, Jarnlo GB, Soderberg B, Persson BM. Kinematic and kinetic gait analysis in the sagittal plane of trans-femoral amputees before and after special gait re-education. Prosthet Orthot Int 2002;26:101–12.
[16] Vanicek N, Strike S, McNaughton L, Polman R. Gait patterns in transtibial amputee fallers vs. non-fallers: biomechanical differences during level walking. Gait Posture 2009;29:415–20.
[17] Roerdink M, Beek PJ. Understanding inconsistent step-length asymmetries across hemiplegic stroke patients: impairments and compensatory gait. Neurorehabil Neural Repair 2011;25:253–8.
[18] Balasubramanian CK, Neptune RR, Kautz SA. Foot placement in a body reference frame during walking and its relationship to hemiparetic walking performance. Clin Biomech 2010;25:483–90.
[19] Houdijk H, Pollmann E, Groenewold M, Wiggerts H, Polomski W. The energy cost for the step-to-step transition in amputee walking. Gait Posture 2009;30:35–40.
[20] Silverman AK, Fey NP, Portillo A, Walden JG, Bosker G, Neptune RR. Compensatory mechanisms in below-knee amputee gait in response to increasing steady-state walking speeds. Gait Posture 2008;28:602–9.
[21] Ventura JD, Klute GK, Neptune RR. The effect of prosthetic ankle energy storage and return properties on muscle activity in below-knee amputee walking. Gait Posture 2011;33:220–6.
[22] Winter DA, Sienko SE. Biomechanics of below-knee amputee gait. J Biomech 1988;21:361–7.
[23] Selles RW, Korteland S, Van Soest AJ, Bussman JB, Stam HJ. Lower-leg inertial properties in transtibial amputees and control subjects and their influence on the swing phase during gait. Arch Phys Med Rehabil 2003;84:569–77.
[24] Selles RW, Bussman JBJ, Wagenaar RC, Stare HJ. Effects of prosthetic mass and mass distribution on kinematics and energetics of prosthetic gait: a systematic review. Arch Phys Med Rehabil 1999;80:1593–9.
[25] Donker SF, Beek PJ. Interlimb coordination in prosthetic walking: effects of asymmetry and walking velocity. Acta Psychol (Amst) 2002;110:265–88.
[26] Tura A, Raggi M, Rocchi L, Cutti AG, Chiari L. Gait symmetry and regularity in transfemoral amputees assessed by trunk accelerations. J Neuroeng Rehabil 2010;7:4.
[27] Roerdink M, Coolen H, Clairbois B, Lamoth CJC, Beek PJ. Online gait event detection using a large force platform embedded in a treadmill. J Biomech 2008;41:2628–32.